$a_0(980) \to \gamma\gamma$ and $f_0(980) \to \gamma\gamma$: a consistent description [1]

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Abstract.

We work out the Linear Sigma Model (LSM) predictions for the 2γ decay rates of the $a_0(980)$, $f_0(980)$ mesons under the assumption that they are respectively the $I = 1$ and $I = 0$ members of the $\bar{q}q$ scalar nonet. Agreement with experimental data is achieved provided we include the contribution of a κ meson with mass $\approx 900 MeV$, and a scalar mixing angle ($\sigma - f_0$ mixing in the $\{|NS>, |S>\}$ basis) $\varphi_s \approx -14°$, as predicted by the model.

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Introduction.

The scalar is the most controversial sector of low energy QCD. In contrast with the pseudoscalars or vector mesons where the corresponding multiplets have been unambiguously established and the hadron properties can be interpreted in terms of constituent quarks or effective theories for low energy QCD, the scalar meson identification faces severe problems.

The Particle Data Group (PDG) [1] candidates for the ground state $\bar{q}q$ scalar nonet are : the $f_0(980)$, $f_0(1370)$ and the recently resurrected $f_0(400-1250)$ (σ?) meson for two sites in the $I = 0$ sector; the $a_0(980)$ and $a_0(1450)$ for the isovector scalar meson, and the $K_0^*(1430)$ for the isospinor scalar meson.

Over the past years experimental evidence has accumulated for the existence of light scalar mesons [2-4]. A reanalysis of data [3] which introduces a phenomenological background phase shift (δ_B) claims the existence of an isovector $\kappa(\approx 900)$ and a light $\sigma(\approx 600)$ isoscalar meson. This phase shift can be naturally interpreted in terms of four-meson interactions within the Linear Sigma Model (LSM). Alternative analysis of the same data [4] arrived to the same conclusion. There exist claims for the existence of an even lighter isoscalar meson $\sigma(400-600)$ in different contexts [4-6], and the existence of two scalar meson nonets has also been suggested [7].

The most important drawback for the identification of the $a_0(980)$ and $f_0(980)$ as the $\bar{q}q$ scalar isovector and isosinglet respectively, is their tiny coupling to two photons. The PDG quotes the averaged values $\bar{\Gamma}(a_0(980) \rightarrow 2\gamma) \times BR(a_0(980) \rightarrow \pi^0\eta) = 0.24^{+0.08}_{-0.07} \, KeV$ and $\bar{\Gamma}(f_0(980) \rightarrow 2\gamma) = 0.56 \pm 0.11 KeV$, as reported by the JADE [8], and Crystal Ball [9] collaborations. In the case of the $f_0(980)$, the experimental result is averaged by the PDG with an estimate by Morgan and Pennington [10].

On the theoretical side, a large amount of work has been done trying to understand the structure of the $a_0(980)$ and $f_0(980)$ mesons. There exist calculations for the $a_0(980), f_0(980) \rightarrow 2\gamma$ decays using a variety of approaches [11-13], in particular, in different versions of the quark model [11]. The generally accepted conclusion, is that the $a_0(980), f_0(980) \rightarrow \gamma\gamma$ decay widths are not consistent with a $q\bar{q}$ structure. Thus, other possibilities such as a molecule picture [12] and a $\bar{q}q\bar{q}q$ structure [13] have been explored and found to be consistent with the tiny coupling to two photons.

Recent data from Novosibirsk [14] and forthcoming experiments at high luminosity ϕ factories, will shed some light on this controversial sector. Eventually, the precise measurement of the two photon decay of the $a_0(980)$ and $f_0(980)$ could discriminate among the various proposals for the lowest lying $\bar{q}q$ scalar nonet.

Recently, scalar meson properties were studied in a Linear Sigma Model which incorporates a t'Hooft interaction [6] . The model predicts that the members of the scalar nonet are: $\{\sigma(\approx 400), f_0(980), \kappa(\approx 900)$ and $a_0(980)\}$, with a scalar mixing angle (in the $\{|NS>, |S>\}$ basis) $\phi_s \approx -14°$. In this work we pursue the study of the implications of the LSM for the scalar mesons phenomenology by computing the $a_0(980), f_0(980) \rightarrow \gamma\gamma$ transitions within the model.

Meson loop contributions to $S \rightarrow \gamma\gamma$

Lorentz covariance and gauge invariance dictates the most general form of the $S \rightarrow \gamma\gamma$ transition amplitude (S denoting a scalar meson) :

$$\mathcal{M}(S \rightarrow \gamma(k, \epsilon) \ \gamma(q, \eta)) = \frac{i\alpha}{\pi f_K} V^S \ (g^{\mu\nu} q \cdot k - k^\mu q^\nu) \eta_\mu \epsilon_\nu. \tag{1}$$

The charged meson (hereafter denoted M) loop contributions to $S \rightarrow \gamma\gamma$ are depicted in Fig.(1). A straightforward calculation yields

$$V_M^S = \frac{2 \ f_K \ g_{SMM}}{m_S^2} \left[-\frac{1}{2} + \xi_M^S I(\xi_M^S) \right], \tag{2}$$

where $\xi_M^S = \frac{m_M^2}{m_S^2}$, and $I(x)$ denotes the loop integral

$$I(x) = \begin{cases} 2\left(\text{Arcsin}\sqrt{\frac{1}{4x}}\right)^2 & x > \frac{1}{4} \\ 2\left(\frac{\pi}{2} + i \ln\left(\frac{1}{\sqrt{4x}} + \sqrt{\frac{1}{4x} - 1}\right)\right)^2 & x < \frac{1}{4}. \end{cases} \tag{3}$$

The decay width is given by:

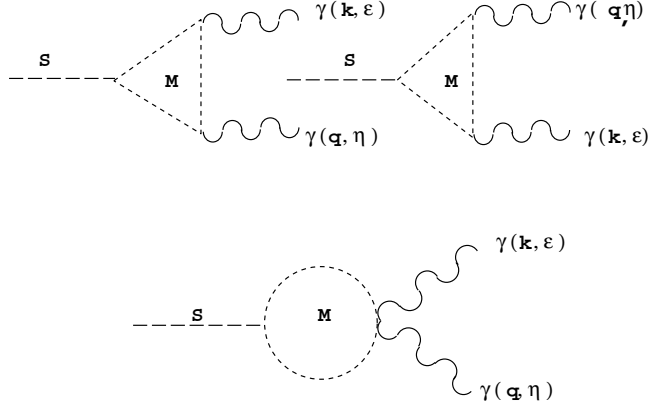$$\Gamma(S \rightarrow \gamma\gamma) = \frac{\alpha^2}{64\pi^3} \frac{m_S^3}{f_K^2} |V^S|^2. \tag{4}$$

Fig.1

Charged meson loop contribution to $S \to \gamma\gamma$.

Let us first analyze the $a_0 \to \gamma\gamma$ transition. The main contribution to this decay comes from a loop of charged K's. The $a_0 K K$ coupling constant is dictated by chiral symmetry [5,6]

$$g_{a_0 K^+ K^-} = \frac{m_{a_0}^2 - m_K^2}{2 f_K}. \tag{5}$$

Using the values reported by the PDG for the a_0, K masses and f_K, we obtain:

$$V_K^{a_0} = 0.42. \tag{6}$$

This is to be compared with the experimental result [1]

$$|V_{exp}^{a_0}| = 0.34 \pm 0.05, \tag{7}$$

extracted from the PDG average by assuming $BR(a_0 \to \pi^0 \eta) = 1$. Within the model we are considering, the only other contribution arises from an isovector scalar meson loop, with the corresponding coupling constant dictated also by chiral symmetry [6]:

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$$g_{a_0\kappa\kappa} = -\frac{m_{a_0}^2 - m_\kappa^2}{2f_\kappa} = -\frac{m_{a_0}^2 - m_\kappa^2}{2(m_K^2 f_K - m_\pi^2 f_\pi)}m_\kappa^2. \tag{8}$$

It is worth noticing the minus sign in Eq.(8). The crucial sign difference between SPP and SSS is generated via the chiral structure $\mathcal{S}+i\mathcal{P}$ entering in the construction of the chirally symmetric Lagrangian [6] ($\mathcal{S}$ and $\mathcal{P}$ denoting the pseudoscalar and scalar nonets respectively). Clearly, K and κ meson contributions will interfere destructively whenever the κ meson mass lie below the $a_0(980)$ meson mass.

The model predicts $m_\kappa \approx 900 MeV$ [6]. Using this value we obtain:

$$V_{LSM}^{a_0} = 0.36 \tag{9}$$

in good agreement with experimental results in Eq.(7).

We can reverse the argument. Considering one standard deviation in the experimental data, the κ meson mass is constrained by the $a_0(980) \rightarrow 2\gamma$ decay to lie in the range $m_\kappa \in [820, 935]$ MeV. The central value in Eq.(7) correspond to $m_\kappa = 870 MeV$. In this respect, it should be mentioned that a kappa mass of 887 MeV was found by Svec and collaborators in ref. [2]. More recently, independent reanalysis of $K\pi$ phase shifts [3,4], conclude $m_\kappa \approx 900 MeV$, whereas theoretical analysis lead to the same conclusion [4-7].

The $f_0(980) \rightarrow \gamma\gamma$ decay can be treated in analogy to $a_0(980) \rightarrow \gamma\gamma$. In this case, however, the mixing between the σ ($f_0(400 - 1200)$?) and $f_0(980)$ must be taken into account. The invariant amplitude describing the process is given by Eqs.(1,2) with $S = f_0$. The observed decay rate

$$\Gamma(f_0 \rightarrow \gamma\gamma) = \frac{\alpha^2}{64\pi^3}\frac{m_{f_0}^3}{f_K^2}|V_{exp}^{f_0}|^2 \cong 0.56 \pm 11 KeV, \tag{10}$$

requires

$$|V_{exp}^{f_0}| = 0.53 \pm 0.05. \tag{11}$$

In the model we are considering, the $f_0(980) \rightarrow \gamma\gamma$ transition gets contributions from loops of scalar and pseudoscalar mesons (K, κ, π). Calculations for the amplitude in this case yields

$$V_M^{f_0} = \left(\frac{2f_K g_{f_0 MM}}{m_{f_0}^2}\right)\left(-\frac{1}{2} + \xi_M^{f_0} I(\xi_M^{f_0})\right), \tag{12}$$

where $\xi_M^{f_0} = \left(\frac{m_M}{m_{f_0}}\right)^2$, $M = \pi, K, \kappa$ and $I(\xi_M^{f_0})$ is given by Eq. (3). Using the PDG values [1] for the K and π masses and $m_\kappa = 870 MeV$, as required by the the central value of the $a_0(980) \to 2\gamma$ decay in Eq.(7), we obtain

$$V_M^{f_0} = f_K \left(\frac{g_{f_0 MM}}{m_{f_0}^2}\right) N_M \tag{13}$$

with $N_K = 1.06$, $N_\kappa = 0.12$, $N_\pi = (-1.10 + 0.48i)$.

We still must fix the f_0 couplings which are affected by its mixing with the σ meson. The physical σ, f_0 fields are related to the $\{|S >, |NS >\}$ isoscalar fields by [5,6]

$$|\sigma >= cos(\phi_s)|NS > \quad - \quad sin(\phi_s)|S >, \tag{14}$$
$$|f_0 >= sin(\phi_s)|NS > \quad + \quad cos(\phi_s)|S >,$$

in such a way that in the zero mixing limit the $f_0(980)$ is purely strange. The scalar mixing angle has been estimated to be $\phi_s \approx -14°$ [6]. Thus, the physical $f_0(980)$ is mostly strange. The more conventional mixing angle θ_s in the octet-singlet basis is related to ϕ_s through $\theta_s = \phi_s - arctan(\sqrt{2})$.

In the zero mixing limit, the model predicts

$$g_{f_0 MM}(\phi = 0) = \frac{m_{f_0}^2 - m_M^2}{2f_M}. \tag{15}$$

To leading order in the mixing angle we can use

$$g_{f_0 MM} = g_{f_0 MM}(\phi = 0) F_M, \tag{16}$$

where F_M stand for the mixing factors

$$F_\pi = sin(\phi_s), \quad F_K = F_\kappa = sin(\phi_s) + \sqrt{2}cos(\phi_s). \tag{17}$$

Pion and kappa loop contributions are suppressed by mixing factors and the large kappa mass respectively. Thus, again, kaon loops dominates the $f_0(980) \to \gamma\gamma$ transition. Numerically, using $\phi_s = -14°$, Eq.(13) yields $V_K^{f_0} = 0.44$, whereas taking all contributions into account we obtain

$$|V_{LSM}^{f_0}| = 0.52, \tag{18}$$

to be compared with experimental data in Eq.(11). Thus, although π and κ contributions are small, they are necessary in order to achieve consistency with the experimental results. Again, the argument can be turned around. The scalar mixing angle is constrained by the experimental errors to lie in the range $[-30°, -5°]$, the central value in Eq.(11) corresponding to $\phi_s = -16°$

Summary.

Summarizing, we compute the $a_0(980), f_0(980) \to 2\gamma$ decay rates in the framework of a LSM, assuming that the $a_0(980), f_0(980)$ mesons are the isovector and isoscalar members of the $\bar{q}q$ nonet. The two photon decays are induced by loops of charged mesons, the dominant contribution arising from a loop of charged K mesons. Agreement with the experimental data is achieved for a $\sigma - f_0$ mixing (in the $\{|NS>, |S>\}$ basis) $\phi_s = -16°$, and a κ mass $m_\kappa = 870 \ MeV$. The required mixing angle and m_κ are consistent with the values predicted by the model [6].

Acknowledgments.

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